Measurements of the polyethylene naphthalate performance as a wavelength shifter in protoDUNE-DP

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DUNE Collaboration Meeting

May 26th 2020

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

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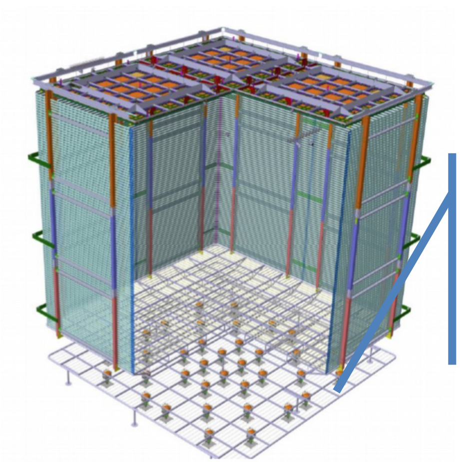
Content

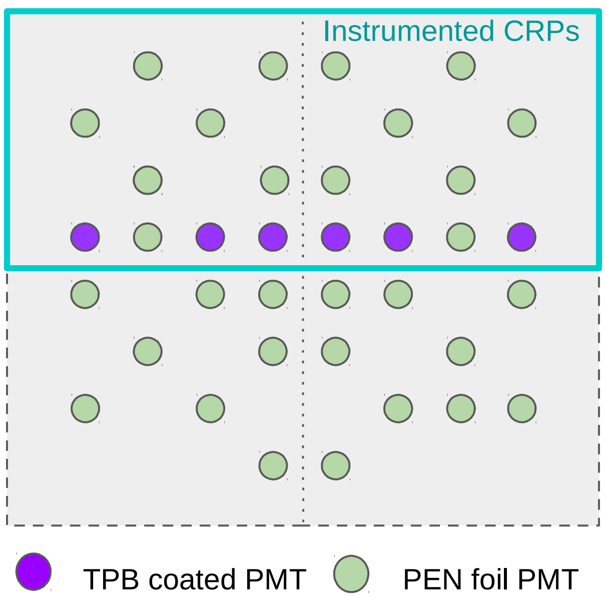
- Introduction:
  - ProtoDUNE Dual-Phase light detection system.
  - Wavelenght shifters on protoDUNE Dual-Phase: Polyethylene naphtalate and TetraPhenyl Butadiene.
- Analysis:
  - Relative measurement of PEN-foil/TPB-coated performance in protoDUNE-DP.
  - Deconvoluting the geometrical differences of foil and coating to obtain the absolute efficencies.
- Results and conclusions.

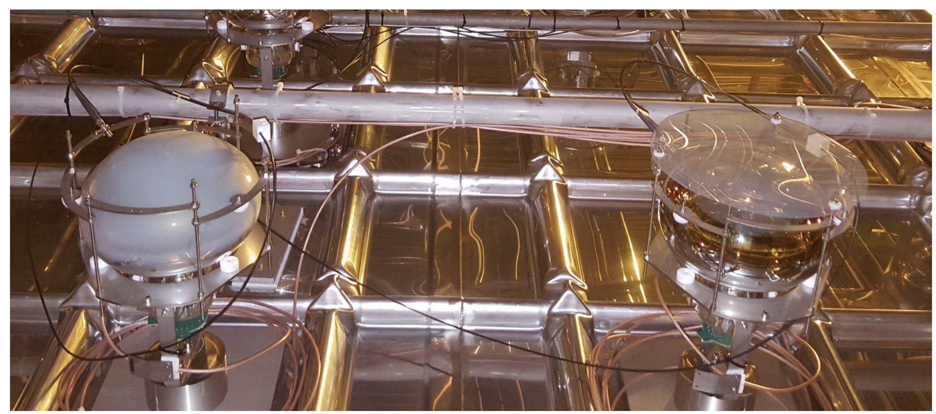
ProtoDUNE Dual-Phase Photon Detection System

- The light detections system provides the event time.
- **It consists on 36 8'' cryogenic PMTs** fully characterized at room and cryogenic temperature [JINST 13 (2018) T10006]
- **Wavelength-shifter:** A combination of PMTs covered with polyethylene naphthalate (PEN) sheets and PMT coated with Tetraphenyl butadiene (TPB) is used.
- Dedicated **light calibration system** (LCS): LED & fiber based [JINST 14 (2019) T04001]

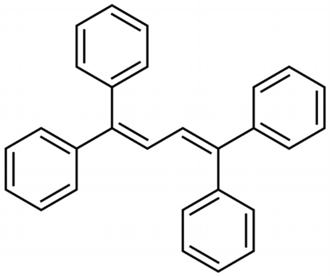


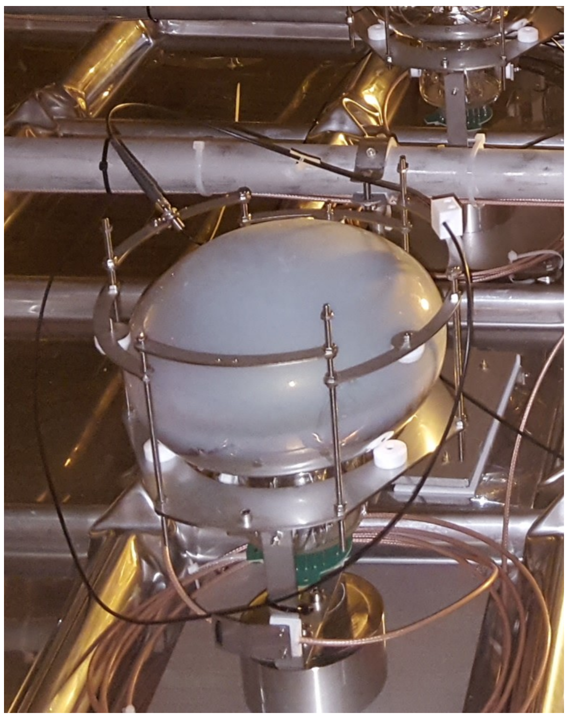
PDS placed below the cathode and the ground grid.



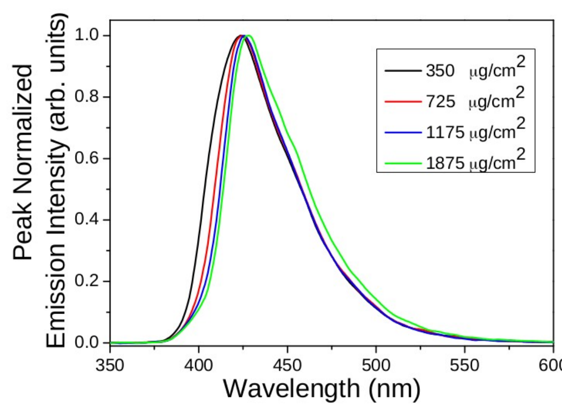


Tetraphenyl butadiene (TPB)

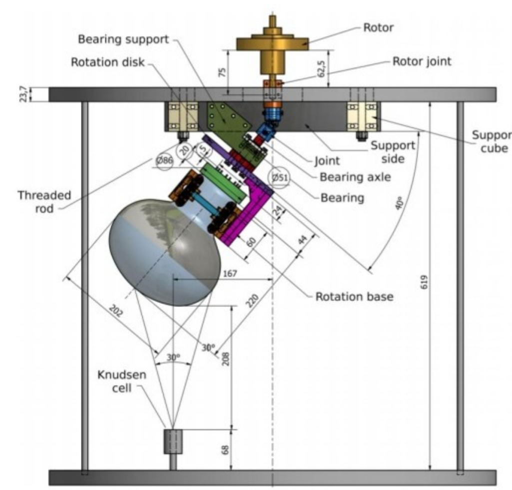




- TPB comes as a “dust” that is deposited over the PMT polished surface using the evaporation system used for Icarus PMTs.
- Coating density is 0.2mg/cm2, ~2um thickness [1].
- TPB re-emission spectrum peaks around 430nm (plot below).
- **TPB coated effective quantum efficiency has been measured at 128nm and room temperature (RT): 0.14±0.02** on 4 of our PMTs, also similar values reported by Icarus collaboration for sand-blasted PMTs[2].
- It is very efficient and widely used in many experiments.

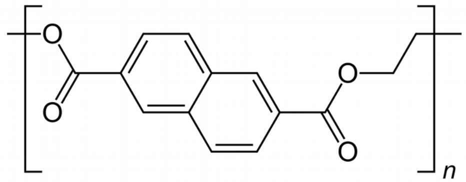


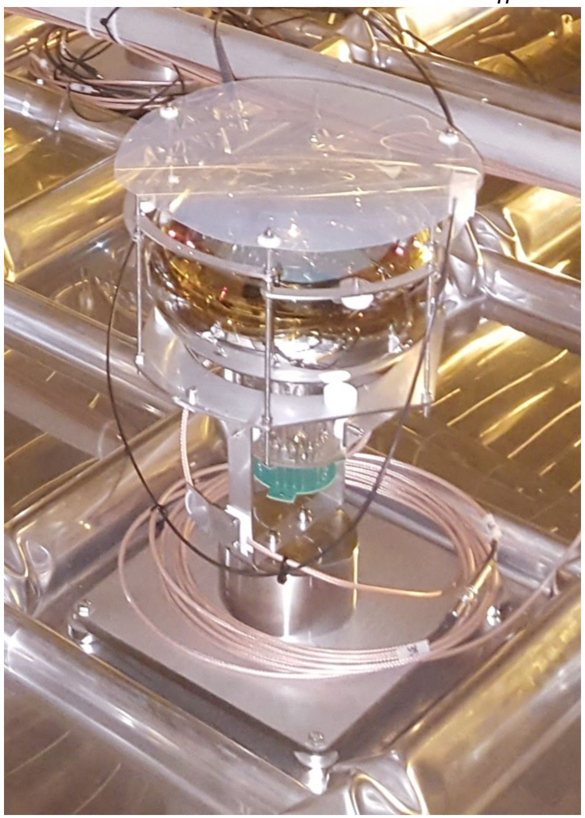
(2013) Francini et al.



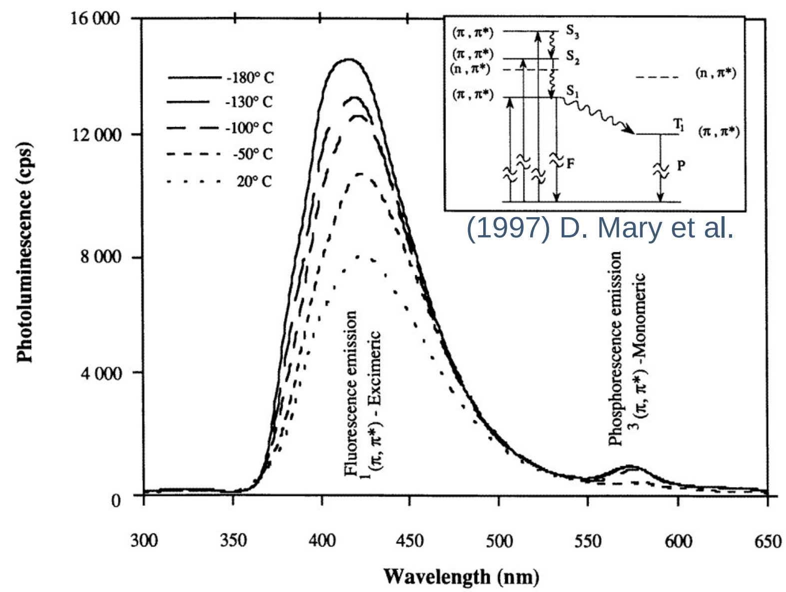
[1] https://indico.fnal.gov/event/18263/contributions/46702/attachments/29115/35923/PMT_Coating_Status.pdf
[2] arXiv:1807.07123 [physics.ins-det]

Polyethylene naphthalate (PEN)





- Thermoplastic similar to PET.
- Circle foils of 240mm diameter and 0.125mm thickness, biaxially oriented.
- They are placed tangent to the PMT glass surface.
- Flourescence lifetime of 20ns at Room Temperature (RT).
- Similar re-emmission spectra to TPB, bottom plot from (1997) D. Mary et al.
- Novel material easy to install and to scale to big detectors like DUNE.
- Efficiency has not been measured at Cryogenic Temperature (CT).



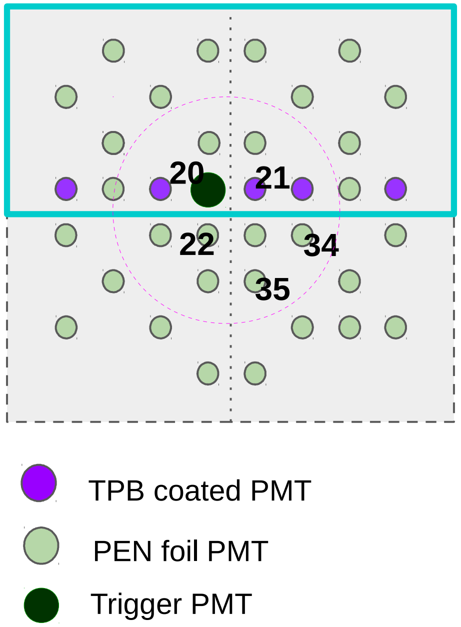
(1997) D. Mary et al.

Analysis

Data

To compare the performace between the two systems, TPB-coated and PEN-foil PMTs, we compare signals of PMTs symmetrically placed w.r.t the trigger PMT and among each other to guarantee that they receive approximately the same amount of light.

- Runs **#2692-#2707** (taken on February 24th 2020).
- Each run at a different gain: (5e6, 1e7, 2e7, 5e7, 1e8)
- Fixed trigger on **channel 20 -TPB coated- gain always at 5e6 and 3950ADC threshold** (minimum amplitude of 50ADC, ~10PEs)
- Waveforms of 16us, 16ns sampling, 200kevt.
- A calibration run is performed before the data taking to ensure we know the operating gain.



- We will consider only PMTs in the vecinity of the trigger PMT, and showing a similar behaviour:

  TPB-PEN pairs to compare: (**21**,22)

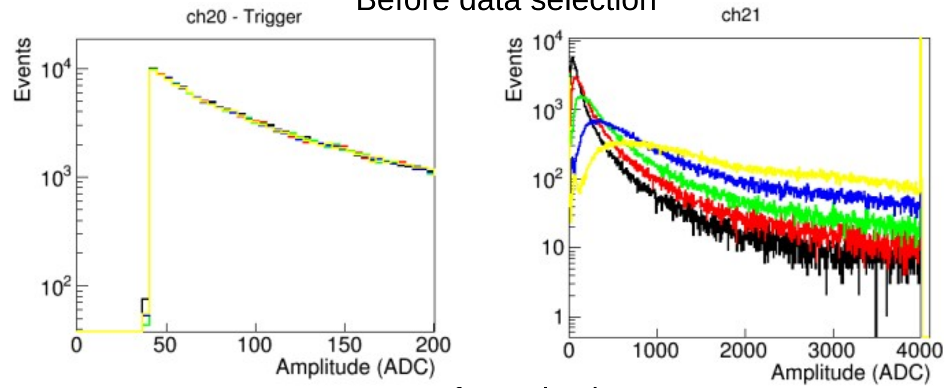
  PEN-PEN pairs to compare: (34,35)

Analysis

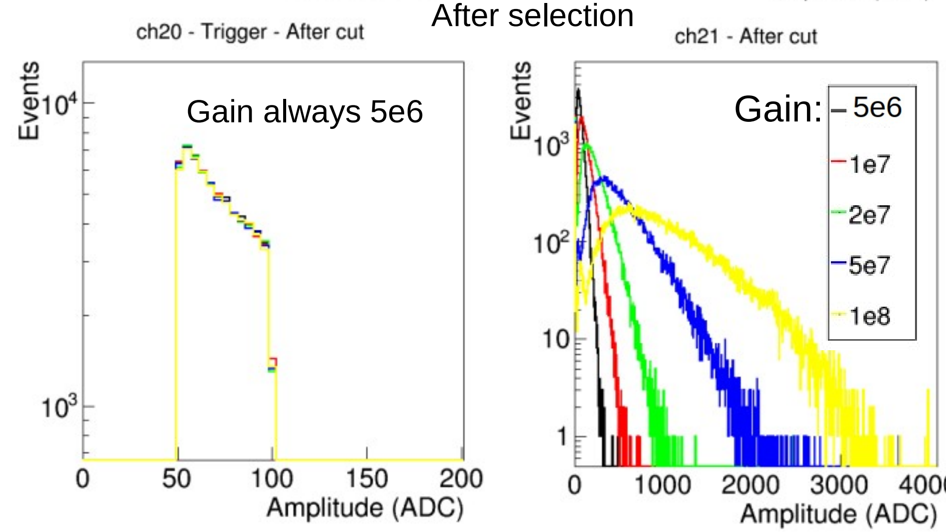
Data selection

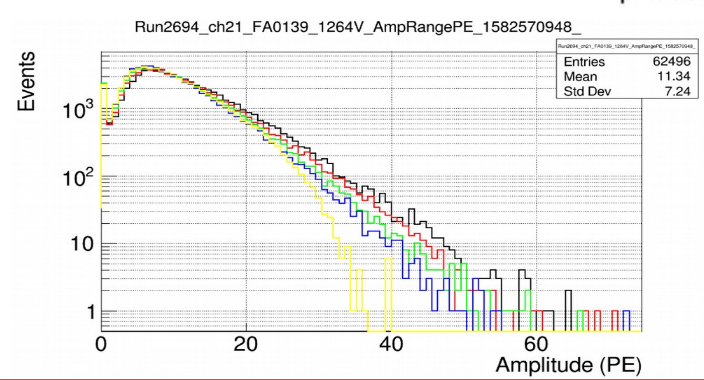
- ADC saturates more at high gains (top right plot).
- Removing events with a signal above 100ADC amplitude (~20PEs) on the trigger channel reduces the ADC saturation below 1% for most PMTs (see bottom plots).
- Since this cut is based only on the trigger-PMT signal, and it is always at the same gain, the events we are selecting are equivalent for all runs (see bottom-left plot).
- We select only 30% of the events.
- PMTs with more than 1% of saturated waveforms after cut are not considered.

Before data selection



After selection





Analysis

PEN TPB performance comparison

- Average detected charge is compared for PMTs symmetrically placed.
- A consistent ratio of 0.218±0.012 is obtained at different gains.
- As a crosscheck, we verify that symmetrically placed PEN PMTs signals show the same average charge.
- This ratio is consistent under different time integration ranges.

- **The ratio of photons detected on PEN-foiled PMTs w.r.t TPB-coated PMTs is 0.218±0.012, considering signals of ~150PE on average on TPB PMTs, on protoDUNE-DP configuration.**

PMT Pair	Gain	Charge (PE)*		
		PMT1	PMT2	Ratio
22-21 PEN-TPB	5E+06	37.1	165.9	0.22
	1E+07	34.4	158.0	0.22
	2E+07	32.0	147.8	0.22
	5E+07	28.7	138.1	0.21
34-35 PEN-PEN	5E+06	37.8	36.1	1.05
	1E+07	32.5	32.7	0.99
	2E+07	29.5	29.6	1.00
	5E+07	26.8	27.0	0.99
	1E+08	25.7	25.7	1.00

*Charge integrated in 3us.

Analysis

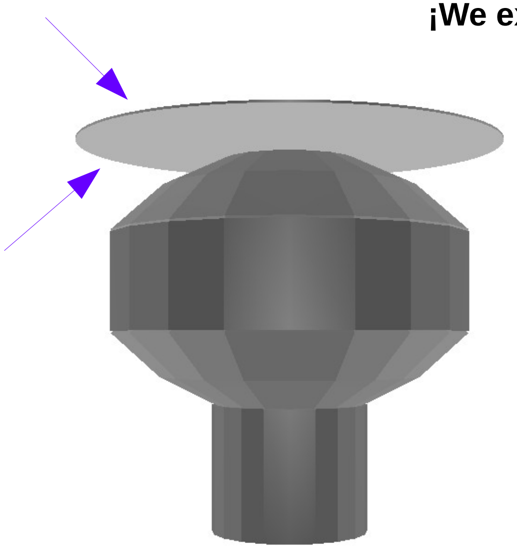
Deconvoluting the geometrical differences

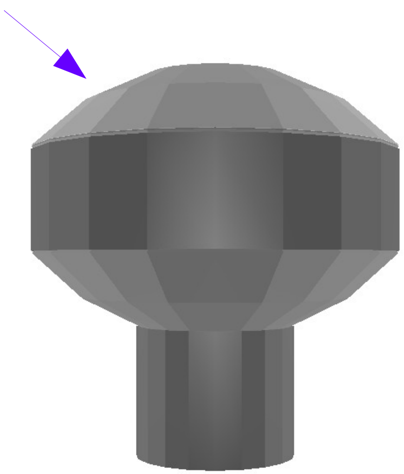
- PEN Foil
  - **γ_{foil}:** #photons arriving to the foil.
- TPB Coating:
  - **γ_{coat}:** #photons arriving to the coating.

$\gamma_{coat}/\gamma_{foil}$ = 0.69 ± 0.16
(see next slide)

Coating has a smaller active surface than foil.

¡We expect more light arriving to the foil!

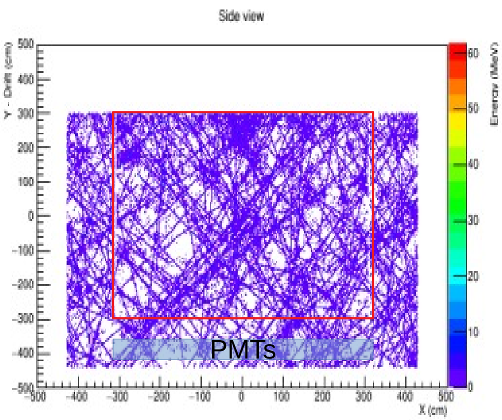


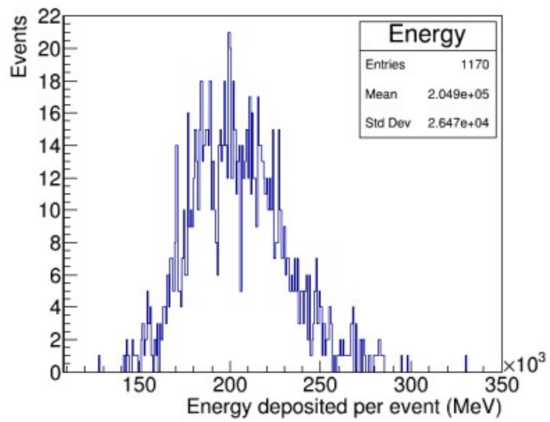


Analysis

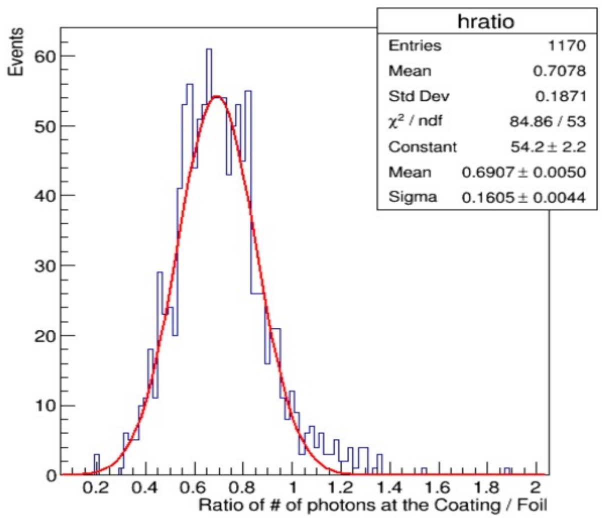
Deconvoluting the geometrical differences

Estimating $\gamma_{coat}/\gamma_{foil}$





- The amount of photons that arrives to the foil and the coating is estimated using Corsika.
- Every event contains all the cosmics crossing the detector in 8ms. See deposited energy of an event in the top plot. ~1200 events are simulated.



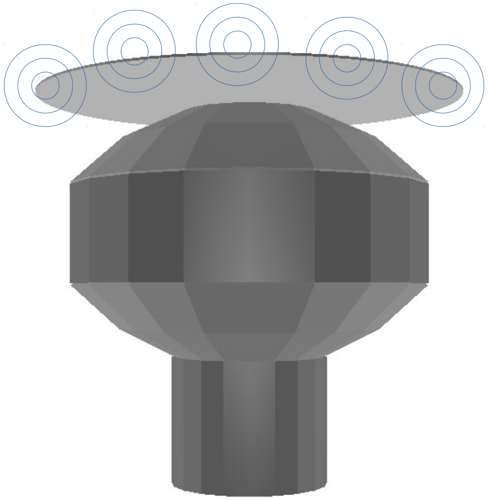
- A light yield of 40kph/MeV is considered (no drift), and photon propagation is simulated using the photon library at 99.9cm of Rayleigh scattering (simulation is still under validation).
- The ratio of photons that arrive to the coating over the foil per event is obtained (bottom plot).
- The sigma of the gaussian is taken as a conservative error:

$$\gamma_{coat}/\gamma_{foil} = 0.69 \pm 0.16$$

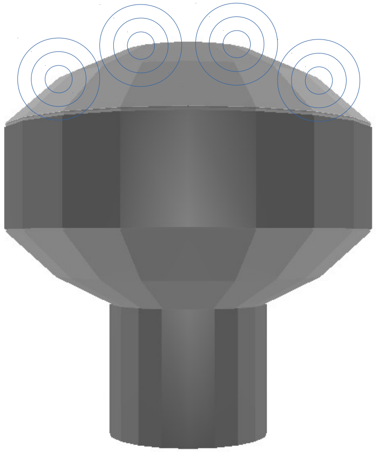
Analysis

Deconvoluting the geometrical differences

- PEN Foil
  - **γ_{foil}:** #photons arriving to the foil.
  - **ε_{PEN}**: PEN re-emission efficiency (128nm)
- TPB Coating:
  - **γ_{coat}**: #photons arriving to the coating.
  - **ε_{TPB}:** TPB re-emission efficiency (128nm).



PEN/TPB re-emission efficiency is the probability for an incoming VUV photon **(at 128nm)** to emit a visible photon.



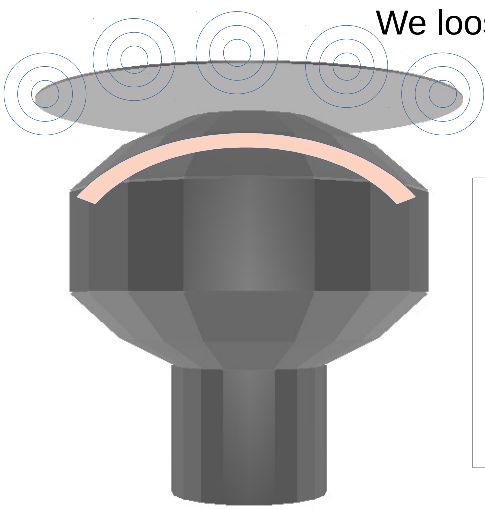
Analysis

Deconvoluting the geometrical differences

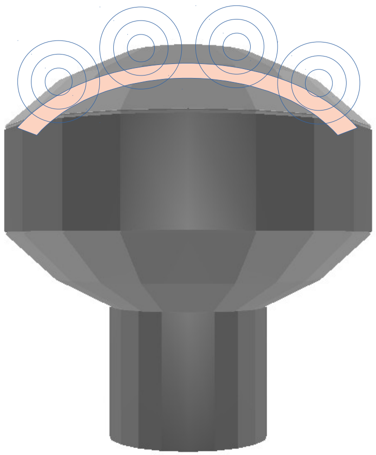
- PEN Foil
  - γ_{foil}: #photons arriving to the foil.
  - ε_{PEN}: PEN re-emission efficiency.
  - Δ_{foil}: Geometrical looses Foil-PC (0.25)

- TPB Coating:
  - γ_{coat}: #photons arriving to the coating.
  - ε_{TPB}: TPB re-emission efficiency.
  - Δ_{coat}: Geometrical looses Coating-PC (0.5)

Light is re-emitted isotropically, and some photons arrive to the photocathode (PC).
We loose more light in the foil w.r.t the coating.



25% of photons isotropically reemited by the foil would arrive to the photocathode (simulated)



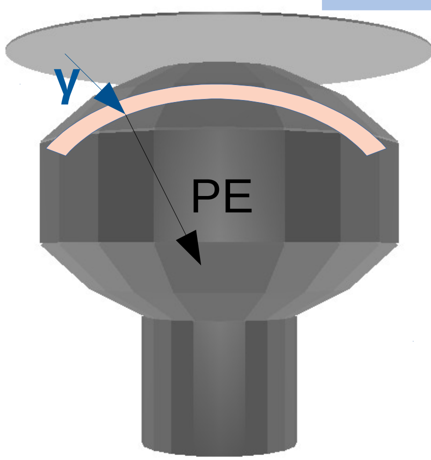
~50% of photons isotropically reemited by the coating would arrive to the photocathode.

Analysis

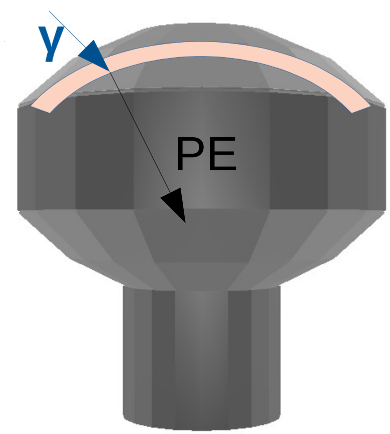
Deconvoluting the geometrical differences

- PEN Foil
  - γ_{foil}: #photons arriving to the foil.
  - ε_{PEN}: PEN re-emission efficiency.
  - Δ_{foil}: Geometrical looses Foil-PC (0.25)
  - QE=0.18±0.01
- TPB Coating:
  - γ_{coat}: #photons arriving to the coating.
  - ε_{TPB}: TPB re-emission efficiency.
  - Δ_{coat}: Geometrical looses Coating-PC (0.5)
  - QE=0.18±0.01

QE efficiency at 430nm has been measured in 3 of our PMTs by Hamamatsu at RT.



18% of the blue photons (430nm) arriving to the photocathode will produce a photoelectron.



Analysis

Deconvoluting the geometrical differences

- PEN Foil
  - **γ_{foil}:** #photons arriving to the foil.
  - **ε_{PEN}**: PEN re-emission efficiency.
  - **Δ_{foil}**: Geometrical looses Foil-PC (0.25).
  - QE=0.18±0.01

- TPB Coating:
  - **γ_{coat}**: #photons arriving to the coating.
  - **ε_{TPB}:** TPB re-emission efficiency.
  - **Δ_{coat}**: Geometrical looses Coating-PC (0.5).
  - QE=0.18±0.01

# of PE emmited by the photo-cathode:

$NPE_{PEN\text{-}FOIL} = \gamma_{Foil}\, \varepsilon_{PEN}\, \Delta_{Foil}\, QE$

$NPE_{TPB\text{-}coat} = \gamma_{coat}\, \varepsilon_{TPB}\, \Delta_{Coat}\, QE$

$$\boxed{\frac{NPE_{PEN}}{NPE_{TPB}} = \frac{1}{\gamma_{coat}/\gamma_{foil}} \frac{\varepsilon_{PEN}}{\varepsilon_{TPB}} \frac{\Delta_{Foil}}{\Delta_{Coat}}}$$

Already measured on data: (0.218±0.12)

Estimated from simulations: (0.69 ± 0.16)

The efficiency we want to obtain.

Results

PEN/TPB relative re-emission efficiency

$$\frac{\varepsilon_{PEN}}{\varepsilon_{TPB}} = \frac{NPE_{PEN}}{NPE_{TPB}} \frac{\gamma_{coat}}{\gamma_{foil}} \frac{\Delta_{Coat}}{\Delta_{Foil}}$$

We can obtain the ratio ε_{PEN} / ε_{TPB} considering:

- NPE_{PEN} / NPE_{TPB} = 0.218±0.012 directly measured in the detector, on signals of ~150PE integrated charge on average.
- γ_{coat} / γ_{foil} = 0.69±0.16 simulated using corsika.
- Geometrical looses: Δ_{Foil} = 0.247 and Δ_{coat} = 0.5 estimated assuming an isotropic re-emission.

$$\frac{\varepsilon_{PEN}}{\varepsilon_{TPB}} = 0.30 \pm 0.08$$

- **We obtain a ratio of efficiencies PEN/TPB of 30%<u> at 128nm and cryogenic temperature.</u>**

-preliminary-

Results

PEN/TPB relative re-emission efficiency

- Our estimation of relative PEN/TPB efficiency at 128nm and CT based on protoDUNE-DP measurements is:

$$\boxed{\frac{\varepsilon_{PEN}}{\varepsilon_{TPB}} = 0.30 \pm 0.08}$$

→ This value relies only in our measurement in the lab, and geometrical factors (introduced with the Monte Carlo simulation).

→ Simulation is still under validation (see presentation by A. Gallego). Future tuning the MonteCarlo parameters might affect these results (not much).

- I haven't found an equivalent measurement on the literature (at 128nm and CT).
- Kuzniak (2019) compared PEN performance w.r.t. TPB coated on glass and PMMA, which is not our case.
- He provided a relative performance of **0.38** for both TPB and PEN placed on glass at 128nm and CT (extrapolating from the literature to go from RT to CT, real measurement is 0.18 at RT).

$$\frac{\varepsilon_{PEN}}{\varepsilon_{TPB}} (Kuzniak, 2019) \sim 0.38$$

-preliminary-

Results

Absolute PEN re-emission efficiency

$QE_{eff,TPB}$

$NPE_{PEN} = \gamma_{Foil}\ \varepsilon_{PEN}\ \Delta_{Foil}\ QE$

$NPE_{TPB} = \gamma_{coat}\ \boxed{\varepsilon_{TPB}\ \Delta_{coat}\ QE}$

$$\boxed{\varepsilon_{PEN} = \frac{NPE_{PEN}}{NPE_{TPB}} \frac{\gamma_{coat}\, QE_{eff,TPB}}{\gamma_{foil}\, \Delta_{Foil}\, QE}}$$

We can obtain the absolute ε_{PEN} considering:

- NPE_{PEN} / NPE_{TPB} = 0.218±0.012 directly measured in the detector.
- γ_{coat} / γ_{foil} = 0.69±0.16 simulated using corsika.
- Geometrical looses Δ_{PEN} =0.247 estimated asuming isotropic re-emission.
- $QE_{eff,TPB}$ = 0.14±0.02 – Measured in Pavia for 4 or our PMTs at RT and 128nm.
- QE = 0.183±0.013 - Provided by Hamamatsu for 3 of our PMTs at RT at 430nm.

- Considering the effective QE of TPB coated PMTs measured in Pavia, we can obtain a PEN absolute efficiency of 0.47.

$$\varepsilon_{PEN} = 0.47 \pm 0.14$$ *Without correcting at CT

- We can apply a correction to extrapolate $Qe_{eff,TPB}$ measurement from RT to CT:
  - We do not expect the PMT QE to change at CT [A. Bueno et al. (2008)].
  - But TPB emission increases around 10% when going to cryogenic tempeterature (measured by Francini et al, 2013).

$$\boxed{\varepsilon_{PEN} = 0.52 \pm 0.15}$$ *At 128nm and CT

-preliminary-

Results

Absolute PEN re-emission efficiency

- If we take into account the effective QE of TPB coated PMTs measured at in the lab at RT, and correcting to CT [Francini et al. (2013)], we can obtain an absolute efficiency of PEN:

$$\boxed{\varepsilon_{PEN} = 0.52 \pm 0.15}$$

- This measurement is not far from the value given by Kuzniak:

$$\varepsilon_{PEN}(Kuzniak, 2019) \sim 0.42$$

- However we must consider that he does not measure this value directly:
  - He takes the absolute value for the TPB from the literature (~0.6 on TPB+PMMA at 250nm and RT, Benson et al, 2018).
  - He used this to deconvolute his relative measurement of 0.27 (PEN vs TPB+PMMA at 250nm and RT), and then extrapolating to 128nm and CT based on the literature.

- Also, on our measurement, by taking an effective QE of TPB-coated PMT measured in Pavía at RT (14%), we are taking implicitely a TPB re-emission efficiency larger than unity at RT:

$$\boxed{\varepsilon_{TPB,RT} = QE_{eff,TPB} / (\Delta_{TPB} QE) \sim 1.5}$$

- , which does not agree with Benson et al, (2018), who measured a TPB re-emmission efficiency of ~0.5 at 128nm and RT.

-preliminary-

References

- A technical note is under preparation, and will be available soon.
- TPB:

R. Francini et al., JINTST 8, P09006 (2013)

C. Benson et al., Eur. Phys. J. C. (2018) 78:329

- PEN:

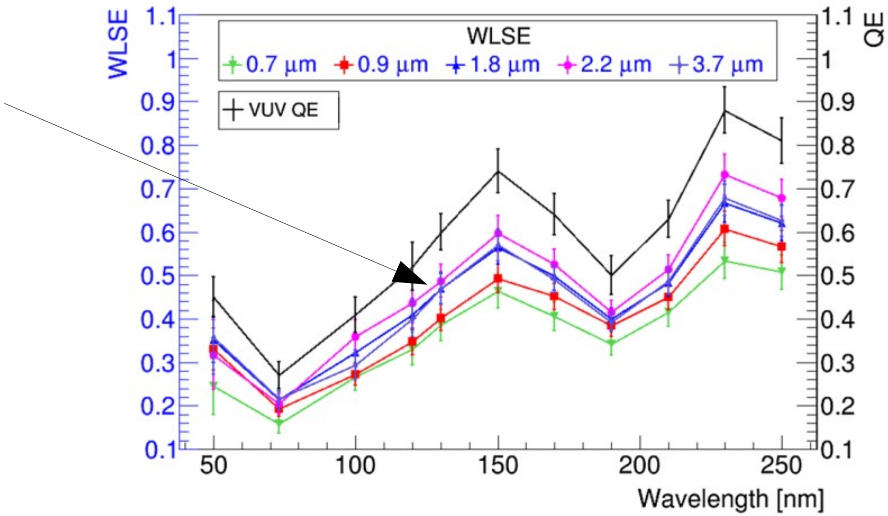
M. Kuzniak et al., Eur. Phys. J. C. (2019) 79:291

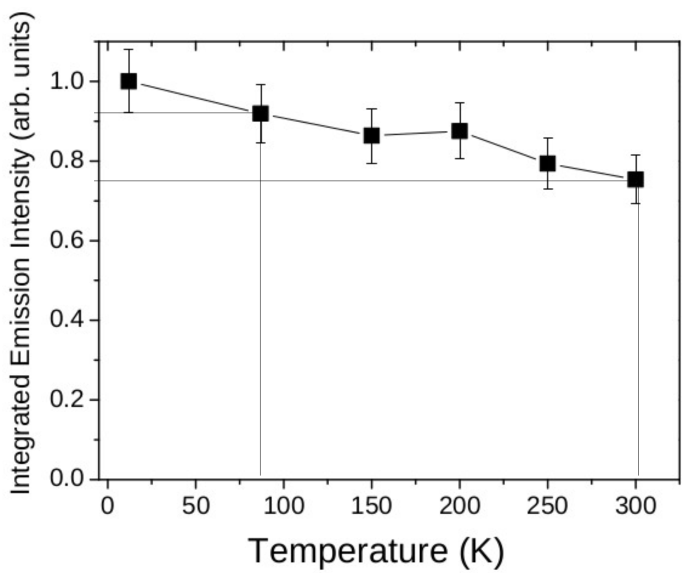
D. Mary et al., J.PHYs. D Appl. Phys. 30, 171 (1997).

D. Mary et al., 2001 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, p. 165 (2001) – PEN degradation when exposed to VUV light.

Backup

What is in the literature? TPB Benson (2018)





Benson (2018):

At 128nm and RT:

- Absoluty QE (intrinsic to the material) of 0.6.
- Best **WLSE** of **0.48** at 2um thickness

Francini (2013):

- Emission increases 10% from RT to 87K (from the text) (Kuzniac considers 20%).
- TPB evaporated on polymeric reflector substrate (VM2000), layer density of 175ug/cm2

What is in the literature? TPB Benson (2018)

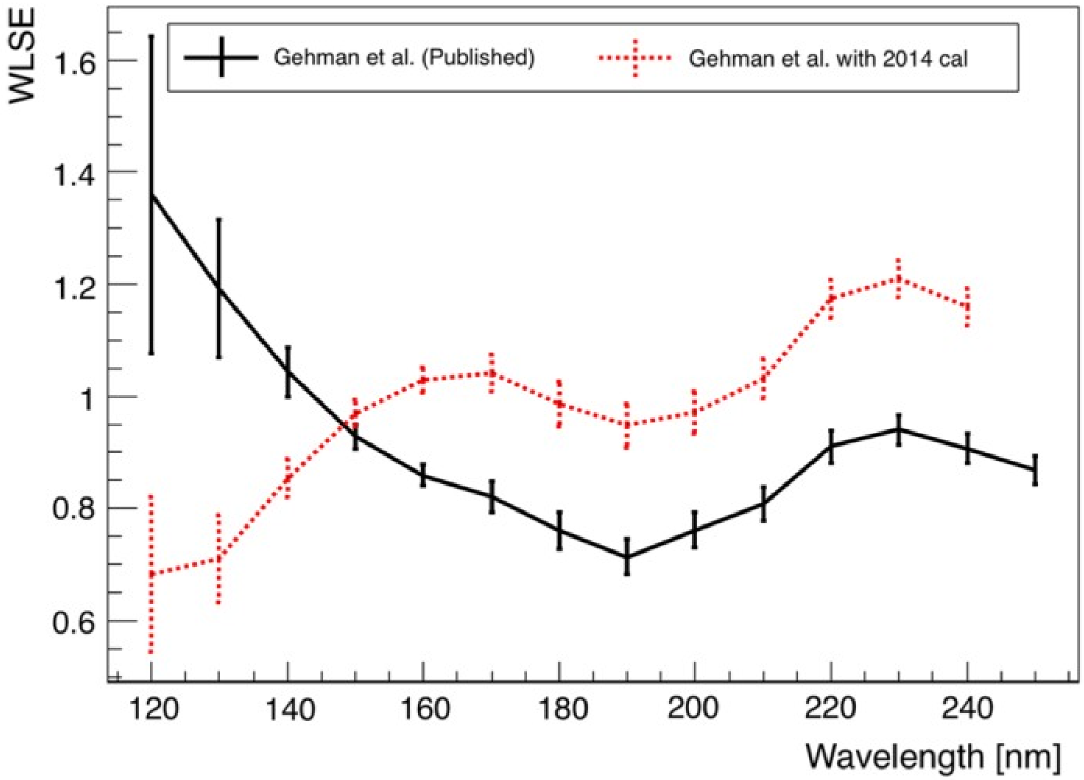
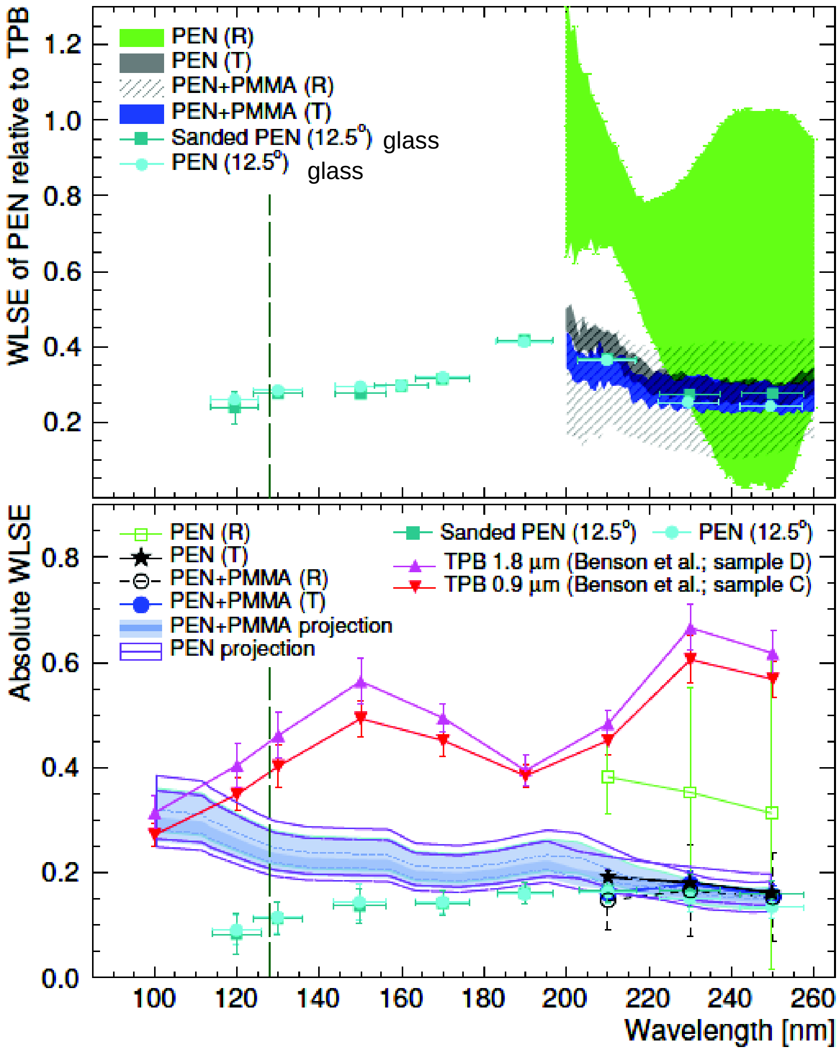


Fig. 22 A comparison of the published results in [16] (solid line) to a reanalysis of the raw data from [16] using the 2014 calibration (dotted line). When the 2014 calibration is applied, the result from [16] has a similar shape as the results from this work. The scale offset is explained in Sect. 8.1.2

Gehman et al reported a TPB efficiency of 100% at 128nm in 2011.

- This is the same team as Benson. It happens that the photodiodo calibration was too old.

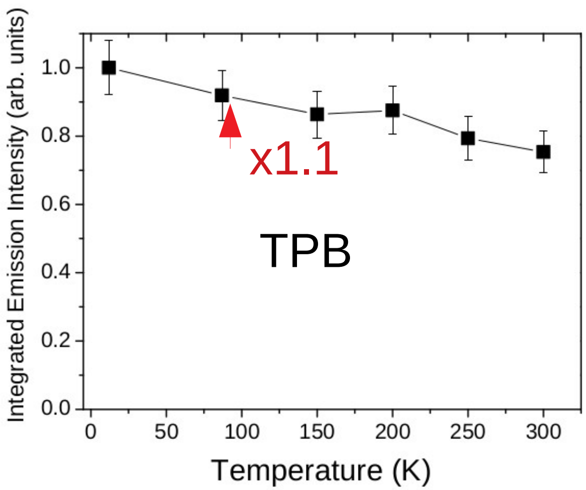
What is in the literature? PEN – Kuzniak (2019)



Sample	293 K 250 nm	293 K 128 nm	87–93 K x1.2 128 nm
TPB+PMMA	0.59(7)	0.43(7)	0.52(10)
PEN+PMMA	0.15(2)	0.24(4)	x1.7 0.40(7)
PEN	0.16(4)	0.25(5)	0.42(8) vs 0.47
PEN (glass)	0.15(3)	0.12(3)	0.20(6)
PEN+PMMA / TPB+PMMA	0.25(5)*	0.56(13)	**0.77(20)**
PEN / TPB+PMMA	0.27(8)*	0.58(15)	**0.80(23)**
PEN(glass) / TPB+glass	0.26(4)*	0.28(4)*	**0.38(7)**
VM2000 / TPB+TTX	0.09		0.317(16)

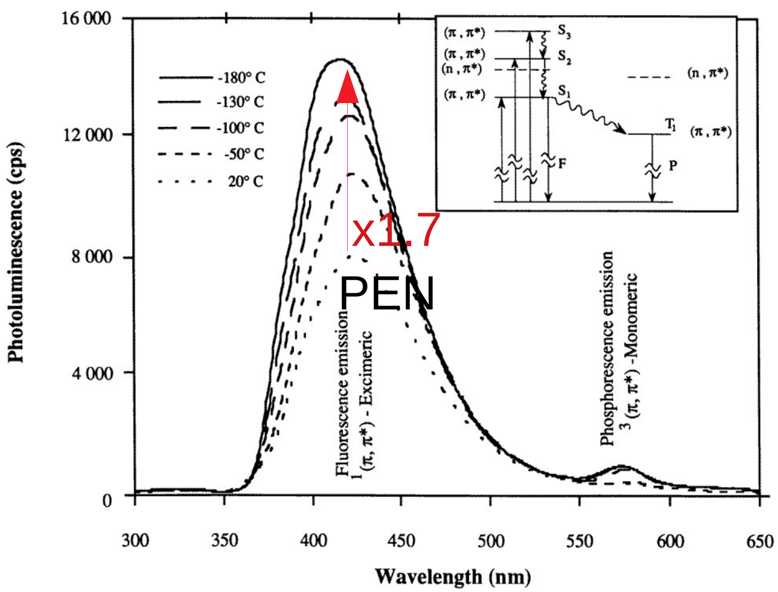
- From Kuzniak (2019)
- Relative PEN TPB efficiency has been measured to be around 0.28-0.58 at RT, extrapolated to **0.38**-0.8 at CT.
- PEN thickness of 0.125mm (same as ours).
- TPB thickness 1.2um

Backup: From RT to CT in Kuzniak



*TPB evaporated on polymeric **reflector** substrate (VM2000), layer density of 175ug/cm2
Excitation waveflength of 128nm

Francini (2013):

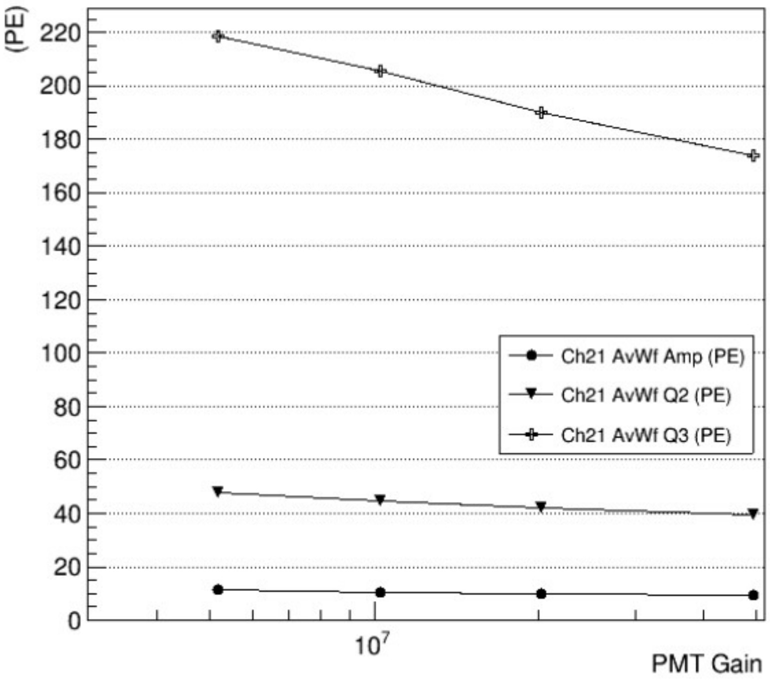


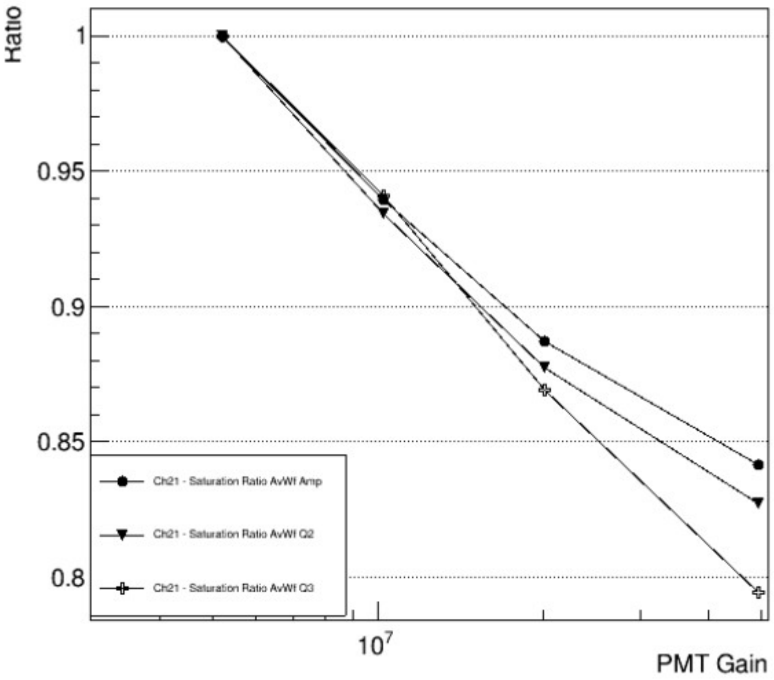
(1997) D. Mary et al.

*excitation wavelength of 300nm

Analysis

PMT response dependence on the gain

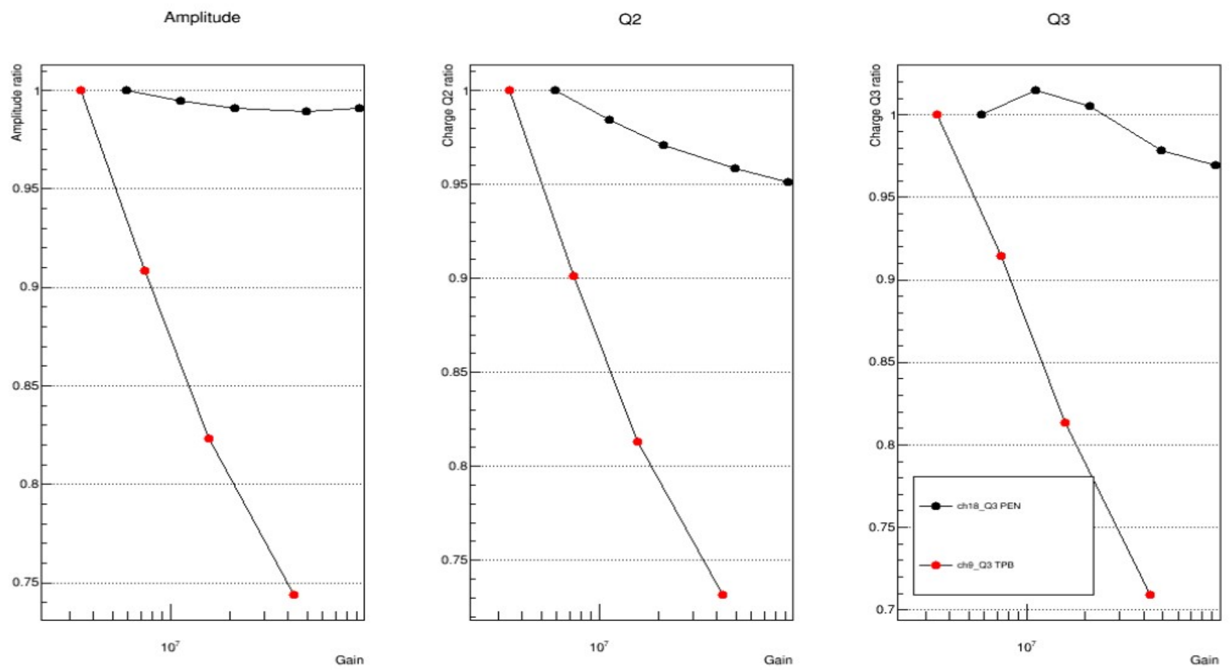




- If we take the average amplitude/charge at different gains, and we correct by the gain measured in the same day, we observe a decay in the number of detected photoelectrons.
- This decay is observed in all three observables (amplitude, charge Q2 and Q3), and in all PMTs.

Analysis

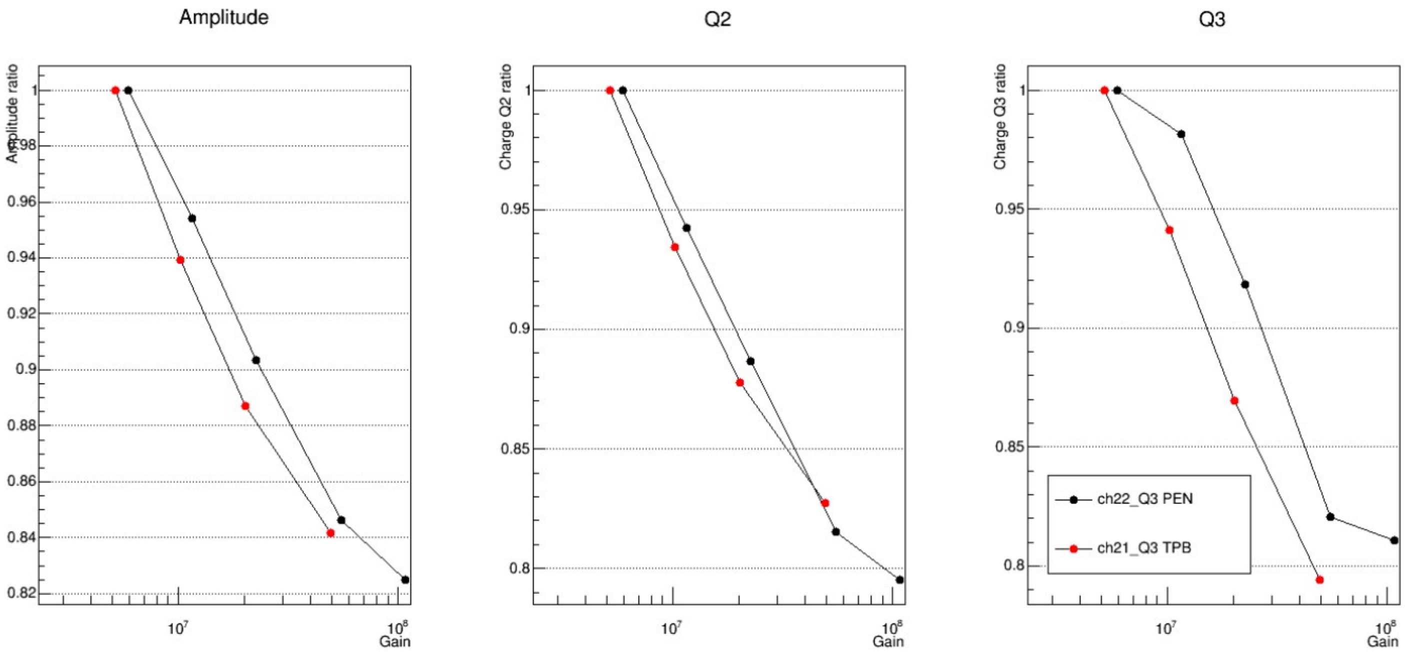
PMT response dependence on the gain



- Not all PMTs show this saturation in the same way. See above two PMTs with a very different behaviour.

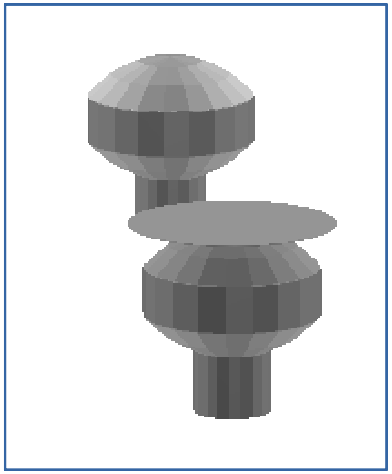
Analysis

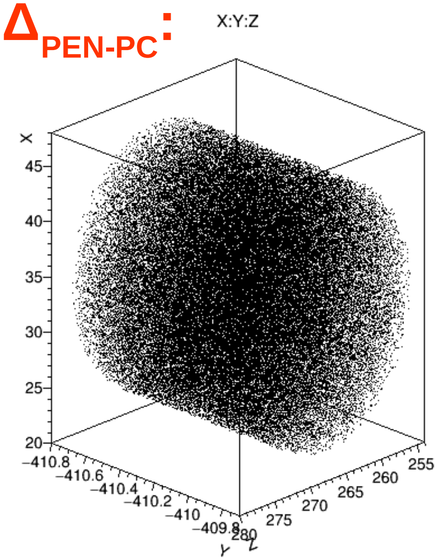
PMT response dependence on the gain



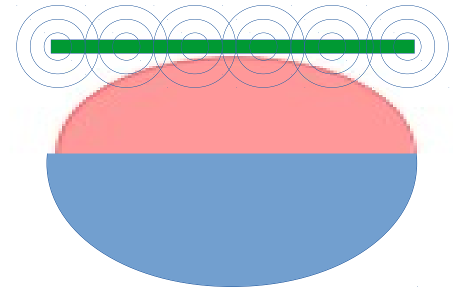
- It is important to compare among PMTs that they show similar behaviour:
  - Only pairs TPB-PEN (22,21) above and PEN-PEN (34,35) show a similar curve and are symmetrically placed.

Back-Up:Computing Δ_{PEN-PC}:

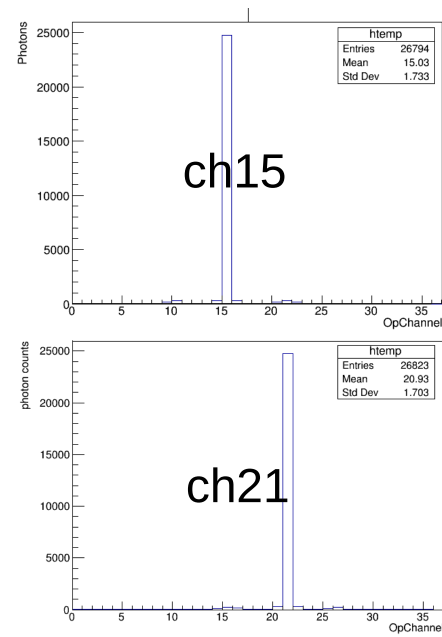




Above: Initial position of simulated photons (within the PEN-Foil geometry).



*Not at scale



Above: # arrival photons per channel. Photons simulated above channel 15 (top), 21 (bottom).

How many photons emmited by the PEN foil (green zone) do arrive to the PMT surface /PhotoCathode (red zone)?
To simulate this, I use TPB coated PMTs (the active volume is in the glass), and generate photons in the position where the PEN foil would be placed.

1e5 photons generated on top of LArSoftChannel 15 (PEN-like)
24753 photons arrive to the red area of the pmt.
Geometry factor: (24.75±0.16)%

1e5 photons generated on top of LArSoftChannel 21 (PEN-like)
24738 photons arrive to the red area of the pmt.
Geometry factor: (24.74±0.16)%